Lunar Phase Angle Effects in the SeaWiFS Measurements of the Moon

Robert A. Barnes

General Sciences Corporation

Beltsville, Maryland 20705

To be submitted as part of the SeaWiFS Postlaunch TM Series

First Draft

June 17, 1999

Abstract

A modification to the lunar reflectance correction in Barnes et al. (1998, 1999) is presented here. This modification accounts for wavelength-dependent differences in the correction for each band, whereas the initial correction is monochromatic. The modification converts the single phase angle dependence curve in Barnes et al. (1998, 1999) into eight curves, one for each band. The effect of the modification is small, changing the values in the original curve by one-part-in-ten or less for each band. The initial correction and the modified correction presented here should be considered as temporary measures. It is assumed that they will be superceded by an improved correction derived from a detailed lunar model currently under development by the United States Geologic Survey.

1. Introduction

The performance specifications for SeaWiFS (Barnes et al., 1994) include a requirement for direct lunar views to monitor instrument stability. The first lunar measurement by SeaWiFS was made on 14 November 1997. Measurements have been made on a monthly basis since then. The SeaWiFS/SeaStar Operations Plan (Gregg et al., 1994) called for measurements during the orbit night nearest 7° lunar phase. Because SeaWiFS makes about 14 orbits of the Earth per day, it is possible to time each measurement to within about one-half degree of 7° lunar phase (Barnes et al., 1998). However, operational requirements, particularly the requirement for at least one orbit between a lunar measurement and a data downlink, have caused some lunar measurements to occur at phase angles that are 2° or more away from the desired angle.

The effects of these angular differences have shown up in the lunar measurement data set. The SeaWiFS Project does not possess a model of the lunar surface that will allow the correction for lunar reflectances at phase angles 2° or more away from 7°. Such a model is under preparation by the United States Geological Survey (USGS) at Flagstaff, Arizona (Kieffer and Anderson, 1998). However, that lunar model may not be sufficiently developed for use by the SeaWiFS Project before the year 2001.

Here, we present a modification of the initial lunar reflectance correction from Barnes et al. (1998, 1999). The modification is based on the set of SeaWiFS measurements through 1 May 1999. The initial correction is monochromatic; that is, the correction is applied in the same manner to all of the SeaWiFS bands. That correction does not account differences in the lunar reflectance at different wavelengths. However, the modified correction presented here is slightly different for each band, providing small changes to the initial correction.

Both corrections should have temporary usefulness, only. It is anticipated that the initial lunar reflectance correction from Barnes et al. (1998, 1999) and the modified correction presented here will be superceded by a new correction that is derived from the lunar model under development at the USGS. Also, both corrections should be considered as approximations to the one that will come from the USGS model. However, these are the best corrections avaiable to us at this time.

2. Initial Lunar Reflectance Equation

The initial lunar reflectance correction is provided in Barnes et al. (1998, 1999). The text in this section provides a description of that correction. It has been adapted from Barnes et al. (1998).

The surface of the moon is not uniformly smooth, containing mountains and craters. Regional variations of the lunar reflectance, such as variations between mare and highlands, also effect uniformity. The variation of the reflectance of the lunar surface with phase angle can be approximated by Hapke's bi-directional reflectance equation (Hapke, 1993). Helfenstein and Veverka (1987) have used Hapke's equation, and a set of six empirically derived constants, to provide a curve of disk integrated reflectance versus phase angle. That curve is shown in Figure 1a. It is given in 1° increments from 0° to 40°. The set of coefficients used by Helfenstein and Veverka (1987) are based in large part on previous measurements of the lunar albedo by Lane and Irvine (1973). A quadratic fit provides an interpolation between the data points in Figure 1a. This interpolation scheme is limited to phase angles (θ's) between 4° and 10°. It is given as

$$f_1(q) = a_0 + a_1 q + a_2 q^2, \qquad (1)$$

where a_0 is 1.287×10^{-1}, a_1 is -6.702×10^{-3} deg^{-1}, a_2 is 2.163×10^{-4} deg^{-2}, and θ is the phase angle in degrees. The quadratic curve agrees with the values from Figure 1a at the 0.1% level. At a phase angle of 7°, $f_1(\theta)$ is 0.09238 The normalizing factor for the lunar reflectance, k_3, is calculated as a ratio

$$k_3 = \frac{f_1(7)}{f_1(q)} = \frac{0.09238}{a_0 + a_1 q + a_2 q^2}. \qquad (2)$$

It corrects to a value of unity at a lunar phase angle of 7°. A plot of k_3 is shown in Figure 1b.

The change in lunar reflectance with phase angle from Helfenstein and Veverka (1987) is monochromatic. The measurements used as a basis for their lunar reflectance model were made at wavelengths from 360 nm to 1060 nm (Lane and Irvine, 1973). Helfenstein and Veverka (1987) used the average of those measurements (over wavelength) to create a single, best-fit lunar reflectance curve at an undefined wavelength, presumably near 500 nm.

3. Data Set

The data set used here is summarized in Table 1. The analysis of Barnes et al. (1998) used a subset of these data, extending from 14 November 1997 to 10 July 1998. The analysis of Barnes et al. (1999) used a subset extending from 14 November 1997 to 4 November 1998. In both of those analyses, the measurements on 13 January 1998 (5.54° lunar phase angle) and 10 July 1998 (5.70° lunar phase angle) were included the data sets. With the measurement on 1 February 1999 (4.88° phase angle), a clear effect was obvious in the measurements.

For trend analyses since the writing of Barnes et al. (1999), these three measurements were removed from the data set. However, the operational constraint that can cause lunar measurements at angles that are different from 7° lunar phase still exist. For example, the lunar measurement on 30 May 1999 was taken at a lunar phase angle of 7.95°. With more problematic phase angles anticipated in future measurements, the decision was made to develop a modified lunar reflectance correction. The correction has been developed using the lunar data from 14 November 1997 through 1 May 1999.

The method for calculating the modification to the reflectance correction is simple. For each band, a regression line is calculated to determine the change in the output of the band with time. This trend line is created without the measurements on 13 January 1998, 10 July 1998, and 1 February 1999. The differences of each of these three measurements from the trend line are determined and plotted versus the lunar phase angle of the measurement. The differences are calculated in fractional terms, that is, as ratios of the measured values to the values calculated from the trend lines. It is assumed that there is a value of unity for measurements with a 7° phase angle, and this assumption gives a fourth value in each data set. For each band, the slope

of the linear regression to these four data points is the basis for the modification. If the original correction is perfect, then the slope of the linear regression (versus phase angle) is zero.

4. Wavelength Dependent Correction for Bands 1 through 6

The data used as a basis for the modified correction are listed in Table 2. These data are summed spectral radiances, as described in Barnes et al. (1998, 1999). The units for the summed radiances (S) are mW cm^{-2} sr^{-1} μm^{-1}. In Table 3, the summed radiances have been normalized to unity at the time of the first lunar image, which is 71.27 days after the first Earth image taken by SeaWiFS on orbit.

Table 3 also gives the average value for the normalized radiances for bands 3 and 4 in the table. These average values are used in a second normalization of the data. The double normalization process was first used in Barnes et al. (1998), where the second normalization was made to the value for band 5. In Barnes et al. (1999), the normalization was made to the average of the values of bands 1 through 6. Here, the second normalization is made to the average of bands 3 and 4. Over the past few months, it has become evident that the trends for bands 1 through 6 are no longer identical to each other. The differences among the trend lines are small but noticeable. Using the average of bands 1 through 6 as a second normalization now causes a small upward trend (that is, an increasing radiometric sensitivity with time) in bands 3 and 4. Since we know of no mechanism to cause upward trends in these bands only, the decision was made to set the slopes for these bands to zero, rather than setting the average slope for the ensemble of six bands to zero.

The lunar time series for bands 1 through 6, with a second normalization to the average of bands 3 and 4, are listed in Table 4. For SeaWiFS band 1, the values in Table 4 are plotted in

Figure 2a and 2b. Figure 2a shows the values from 15 of the 18 lunar measurements, that is, those without the 3 low phase angle measurements. Figure 2a also shows the line fitted to the 15 points. The legend within Figure 2a gives the slope (a_1) and intercept (a_0) determined from the linear regression. Figure 2b shows the 3 low phase angle measurements from band 1 plus the linear regression from Figure 2a. It is the difference between the 3 data points and the fitted line in Figure 2b that is the basis for the modification for band 1.

Figures 2c and 2d show the results for band 6. The formats for Figures 2c and 2d duplicate those for Figures 2a and 2b. And, in the same manner, it is the difference between the 3 data points and the fitted line in Figure 2d that is the basis for the modification for band 6. A quick inspection of Figure s 2b and 2d shows the data points for band 1 to be above the fitted line and the data points for band 6 to be below the line. As a result, the modification for band 1 (412 nm) will be opposite in sign from that for band 6 (670 nm). Also, the scatter of the data points about the fitted line in Figure 2c is about twice that of the data in Figure 2a.

Figures 2e and 2f give the lunar phase angle for each measurement in the data set. The data points in the two figure panels are the same. They have been included as visual references to link the phase angles with the measurements results in Figures 2a through 2d.

Figure 3 shows the differences of the measured values from the linear regressions for SeaWiFS bands 1 through 6. The differences are given as the ratios of the measured values to the calculated ones. In Figure 3, the abscissa is the lunar phase angle. For band 1, the measured values are greater than those from the trend lines, and for band 6, the measured values are smaller. This follows the results shown in Figures 2b and 2d. Each panel in Figure 3 contains its own fitted line, which is derived from a linear regression. The intercept (b_0) and the slope (b_1) for the line are shown in the panel.

There is the assumption in this analysis that the differences of the measured values from the linear regressions comes exclusively from the phase angle effect. Based on this assumption, the value at 7° must be unity. In other words, there is no difference between the measured and calculated values at that angle. To ensure that the regression lines in Figure 3 pass through unity at 7° phase, the value of unity at 7° phase angle has been put into the data set five times. The values in Figure 3 at 7° lunar phase angle are not measured results. Technically, they are not data. Their existence comes from the underlying assumption for this analysis.

There is a pattern to the trend lines in Figure 3. For band 1 (412 nm) there is a negative slope in the regression line. At longer wavelengths, the slopes are flat (at 490 and 510 nm) and positive (at 670 nm). Such a wavelength dependent pattern cannot be removed by the normalization processes for the SeaWiFS measurements of the moon.

The modification to the lunar reflectance correction is applied as a linear multiplier

$$k_3^* = k_3\left[1 - d_B(q - 7)\right] \tag{3}$$

$$k_3^* = \frac{0.09238}{a_0 + a_1 q + a_2 q^2}\left[1 - d_B(q - 7)\right], \tag{4}$$

where δ_B is different for each SeaWiFS band. The values for δ_B for bands 1 through 6 are listed in Table 5. They are the slopes (b_1's) from the linear regressions in the 6 panels in Figure 3, and they have units of deg^{-1}.

Figure 4 shows the modified lunar reflectance corrections for SeaWiFS bands 1 and 6. The corrections factors for these bands are calculated using Equation (4). The original correction factor is calculated using Equation (2). As shown in Figure 4, the differences of the modified correction factors from the original ones are relatively small. In future processing, the correction factor k_3* in Equation (4) will be substituted for the factor k_3 in Equation (2).

However, for the analysis here, the values of $[1-\delta_B(\theta-7)]$ are applied to the normalized results in Table 4. The values of $[1-\delta_B(\theta-7)]$ are listed in Table 6 along with the corresponding dates and lunar phase angles. They are multiplied by the corresponding values in Table 4. The result of these calculations is Table 7, which is the same as Table 4, except that the modification has been applied. Table 7 also contains lunar results for 30 May 1999, which were not used in the derivation of the values if δ_B.

The normalized radiances in Table 7 are plotted in Figure 5. Each panel in Figure 7 contains 19 data points, including the low phase angle measurements on 13 January 1998, 10 July 1998, and 1 February 1999. Each panel also contains a linear regression of the data and the coefficients for the intercept (c_0) and slope (c_1) for that regression. For the period from November 1997 to May 1999, Figure 5 shows that the radiometric sensitivity of SeaWiFS bands 1 and 6 have decreased by about 0.7% with bands 2 and 5 decreasing by a lesser extent. However, these results are based on the assumption that there has been no change in the radiometric sensitivities of bands 3 and 4.

5. Wavelength Dependent Correction For Bands 7 and 8

The modified lunar reflectance corrections for bands 7 and 8 are derived in the same manner as those for bands 1 through 6. However, the fitted curves for bands 7 and 8 are not single straight lines as are those for bands 1 through 6. The curves for bands 7 and 8 are based on the second order polynomials in Barnes et al. (1999). Table 8 gives the summed radiances for bands 7 and 8. Table 8 is set up in the same manner as Table 2, except for the difference in bands. Table 9 gives the data for bands 7 and 8 after normalization to unity for the first lunar measurement. The rightmost column of Table 9 gives the averages for the values from bands 3

and 4. This column is the same as the corresponding column in Table 3. Finally, Table 10 gives the measurements from bands 7 and 8 normalized to the averages for bands 3 and 4. Table 10 is the same as Table 4, except for the difference in bands. The values in Table 10 are used to provide the modified reflectance correction for bands 7 and 8.

For SeaWiFS band 7, the values in Table 10 are plotted in Figure 6a and 6b. Figure 6a shows the values from 15 of the 18 lunar measurements, that is, from those without the 3 low phase angle measurements. Figure 6a also shows a fitted line to the 15 points. The fitted line is a combination of two curves. The first curve is a quadratic fit derived using the data from 14 November 1997 through 4 November 1998. The coefficients from this fit are listed in Table 11. These are the 12 data points discussed in Barnes et al. (1999). The second curve is a horizontal line extending from day 485 after the first SeaWiFS image to day 604. With the scatter in the data in Figure 6a, it is difficult to determine whether the downward trend indicated by the last two data points (31 March 1999 and 1 May 1999) is real. Figure 6b shows the 3 low phase angle measurements from band 7 plus the fitted curve from Figure 6a.

Figures 6c and 6d show the same results for SeaWiFS band 8. The formats for Figures 6c and 6d duplicate those for Figures 6a and 6b. The fitted line in Figures 6c and 6d) is also a combination of two curves. In Figure 6c, the first curve is derived using the data from 14 November 1997 through 4 November 1998. The coefficients from this fit are listed in Table 11. The second curve is a quadratic that has been fitted from day 435 to day 604. Figures 6e and 6f give the lunar phase angle for each measurement in the data set. The data points for Figures 6e and 6f are the same. They have been included as visual references to link the phase angles with the measurement results in Figures 6a through 6d.

Figure 7 shows the differences of the measured values from the linear regressions for SeaWiFS bands 7 and 8. The differences are given as the ratios of the measured values to the calculated ones. Each panel has its own fitted line, which is derived from a linear regression. The intercept (e_0) and slope (e_1) for the line are shown in the panel. The values for δ_B for bands 7 and 8 are listed in Table 5. They are the slopes (e_1's) from the two panels in Figure 7.

The values of $[1-\delta_B(\theta-7)]$ for bands 7 and 8 are listed in Table 12 along with the corresponding dates and lunar phase angles. These are multiplied by the corresponding values in Table 10, and the result of these calculations is Table 13, which is the same as Table 10, except that the modification has been applied. Table 13 also contains lunar results for 30 May 1999, which were not used in the derivation of the values if δ_B.

The values in Table 13 are plotted in Figure 8. For each panel in Figure 8, there is a fitted line which is derived from two quadratic curves. The first curve comes from a second order regression to the data from 14 November 1997 to 4 November 1998 (the first 12 points in the data set). The second curve comes from a second order regression to the data from 5 September 1998 through 30 May 1999 (the last 10 points in the data set). Both curves overlap, containing the data points from 5 September 1998, 5 October 1998, and 4 November 1998. The two curves are joined into a single result at day 395 after the first lunar image on orbit (5 October 1998). To get agreement between the two curves at day 395, the offset (f_0) for the second curve has been adjusted by about 0.0005.

For each band, the offset for the first curve in each panel remains unchanged, since the first curve can be used to extrapolate the trend for the band back to day zero. In Figure 8, the curves for each band are calculated in the same manner. The agreement between the two curves

for each band is extraordinarily good, indicating a significant contribution from serendipity. Such a good agreement between the fitted curves is not guaranteed in the future.

6. Band7/Band8 Ratios

The ratio of the output SeaWiFS band 7 relative to band 8, the band7/band8 ratio, is a central part of the SeaWiFS atmospheric correction. Thus, it is very important to account for instrumental changes that affect that ratio. The changes in that ratio, derived from SeaWiFS lunar measurements, is plotted in Figure 9a. The curve in Figure 9a is derived from the coefficients for bands 7 and 8 in Table 14. To get a value of unity at the first day of SeaWiFS measurements on orbit (day 0), the curves for band 7 are divided by 1.00885 and the curves for band 8 are divided by 1.02426. Both of these constants come from Table 14.

The curve for the band7/band8 ratio in Figure 9a is calculated from the band 7 and band 8 curves described above,. The data points in Figure 9a come from the values in Table 13. As with the fitted curves, the values for band 7 are divided by 1.00885 and the values for band 8 are divided by 1.02426.

It is also possible to calculate the band7/band8 ratio from SeaWiFS measurements of the sun via the onboard solar diffuser. This requires a modification to the azimuth angle correction presented in Barnes et al. (1999). In that paper, the azimuth correction was a parabola with a value of unity at 0° azimuth and a value of approximately 0.95 at 6° on either side of zero. That correction is equivalent to

$$K_{DIFF} = 10\cos(f), \qquad (5)$$

where K_{DIFF} is the diffuser azimuth correction (dimensionless) and ϕ is the azimuth angle in degrees. This correction works well for SeaWiFS band 8 (Barnes et al., 1999), since it was

derived from the laboratory measurements for this band. However, the trends for the other bands show features that repeat over time, features with a definite azimuthal dependence. To remove these features, a minor modification to Equation (5) is applied

$$K_{DIFF} = 10\cos\left(f + d_f\right), \qquad (6)$$

where δ_ϕ is a small adjustment tuned for each band. For band 8, δ_ϕ is 0.0°, and for band 7, δ_ϕ is 0.3°. With this adjustment, it is possible to calculate the time dependent changes in the solar diffuser readings. The band7/band8 ratios from the solar measurements are plotted in Figure 9b, along with the lunar based curve.

The solar data are normally set to a value of unity on the first day of measurements with the diffuser, that is, on day 5 after the first SeaWiFS image of the Earth. To get agreement between the lunar and solar data, the band7/band8 ratio results from the solar measurements have been multiplied by 0.9969. This multiplier creates the best agreement, on the average, between the lunar and solar measurements. Other normalizations of the solar data are possible, such as a normalization on the first day of lunar measurements (day 71 after the first image). For Figure 9b, it is assumed that all of the solar measurements are equally important, so the average difference between the two trend lines is chosen for normalization.

7. References

Barnes, R. A., W. L. Barnes, W. E. Esaias, and C. R. McClain, 1994: Prelaunch Acceptance Report for the SeaWiFS Radiometer, NASA TM 104566, Vol. 22, 32 pp.

Barnes, R. A., R. E. Eplee, Jr., and F. S. Patt, 1998: SeaWiFS measurements of the moon, in Sensors, Systems, and Next Generation Satellites II, H. Fujisada, ed., Proc. SPIE, 3498, 311-324.

Barnes, R. A., R. E. Eplee Jr., F. S. Patt, and C. R. McClain, 1999: Changes in the radiometric sensitivity of SeaWiFS determined from lunar and solar-based measurements, Appl. Opt., 38, xxx-xxx.

Gregg, W. W., F. S. Patt, and R. H. Woodward, 1994; SeaWiFS/SeaStar Operations Plan, SeaWiFS internal document (March 1994), 29 pp.

Hapke, B, 1993: Theory of Reflectance and Emittance Spectroscopy, New York, Cambridge University Press, 455 pp.

Helfenstein, P. and J. Veverka, 1987: Photometric properties of lunar terrains derived from Hapke's equation, Icarus, 72, 342-357.

Kieffer, H. H., and J. M. Anderson, 1999: Use of the moon for spacecraft calibration, in Sensors, Systems, and Next Generation Satellites II, H. Fujisada, ed., Proc. SPIE, 3498, 325-336.

Lane, A. P., and W. M. Irvine, 1973: Monochromatic phase curves and albedos for the lunar disk," Astron. J., 78, 267-277.

Table 1. Dates, times, and spacecraft locations for the SeaWiFS lunar measurements. The spacecraft locations are given in km from the center of the Earth.

Date	Time (UT)	Days After First Image	Lunar Phase Angle (deg)	Spacecraft Location [X direction] (km)	Spacecraft Location [Y direction] (km)	Spacecraft Location [Z direction] (km)
14 Nov 1997	22:50:09	71.27	6.75	4122.0	5569.9	1481.3
14 Dec 1997	12:18:26	100.83	7.03	945.1	6757.2	1912.9
13 Jan 1998	01:44:52	130.39	5.45	-2526.7	6418.1	1632.6
10 Feb 1998	21:02:36	159.19	6.65	-5300.9	4452.4	1518.7
12 Mar 1998	13:46:08	188.89	6.72	-6900.6	1243.0	1025.1
12 Apr 1998	10:29:28	219.75	6.66	-6533.4	-2662.4	-692.8
11 May 1998	01:33:05	249.38	7.10	-4295.4	-5498.8	-1265.3
10 Jun 1998	13:18:49	278.87	6.43	-1021.3	-6823.1	-1638.3
10 Jul 1998	01:04:02	308.36	5.70	2439.1	-6317.3	-2099.9
5 Sep 1998	23:53:40	366.31	6.52	6847.7	-1634.2	-847.2
5 Oct 1998	10:02:19	395.73	6.69	6865.3	1730.2	339.9
4 Nov 1998	12:40:20	425.84	6.55	5104.8	4629.6	1644.3
4 Dec 1998	00:24:52	455.33	7.03	2246.0	6361.6	2166.3
2 Jan 1999	13:47:04	484.89	6.73	-1052.7	6536.2	2525.9
1 Feb 1999	01:27:59	514.38	4.88	-4177.4	5247.9	2281.4
2 Mar 1999	21:20:16	544.20	7.38	-6600.0	2439.7	834.9
31 Mar 1999	09:53:40	572.73	7.01	-6998.4	-1009.1	482.4
1 May 1999	11:31:15	603.38	6.92	-5306.4	-4525.2	-1281.7
30 May 1999	21:22:41	633.21	7.95	-2243.4	-6420.0	-2005.6

Table 2. Summed spectral radiances for the SeaWiFS lunar measurements. The units for the summed radiances (S_{CORR}) are mW cm^{-2} sr^{-1} um^{-1}. The radiances in the table have been corrected for the set of factors in Barnes (1998, 1999), including the original lunar reflectance correction factor, k_3.

Days After First Image	Lunar Phase Angle (deg)	S_{CORR} Band 1	S_{CORR} Band 2	S_{CORR} Band 3	S_{CORR} Band 4	S_{CORR} Band 5	S_{CORR} Band 6
71.27	6.75	361.400	436.899	505.525	503.294	534.833	514.183
100.83	7.03	360.448	435.829	504.828	502.434	534.658	514.436
130.39	5.45	360.060	434.954	502.781	500.398	530.952	508.950
159.19	6.65	360.991	436.972	505.942	503.987	535.310	513.848
188.89	6.72	363.838	440.433	510.146	507.447	538.794	517.690
219.75	6.66	358.095	433.813	502.371	500.617	531.340	509.327
249.38	7.10	357.125	432.099	500.830	499.453	529.850	508.498
278.87	6.43	361.212	437.112	506.623	504.410	535.031	512.414
308.36	5.70	360.983	436.578	505.455	503.029	533.482	509.814
366.31	6.52	361.596	438.244	508.464	505.616	536.721	514.404
395.73	6.69	362.012	438.311	508.548	506.357	537.662	515.550
425.84	6.55	361.635	438.507	508.418	506.291	537.518	515.171
455.33	7.03	363.922	441.132	511.944	510.170	540.961	518.909
484.89	6.73	359.042	434.454	504.448	502.360	533.461	511.137
514.38	4.88	358.683	433.818	502.619	500.265	529.569	505.685
544.20	7.38	356.848	432.205	502.651	500.553	531.465	509.631
572.73	7.01	367.225	445.032	516.799	514.754	546.245	523.298
603.38	6.92	357.164	433.152	502.867	501.037	530.680	508.466

Table 3. Normalized spectral radiances for the SeaWiFS lunar measurements. The radiances have been set to unity at the date of the first lunar measurement. The rightmost column gives the average value for bands 3 and 4.

Days After First Image	Lunar Phase Angle (deg)	Band1	Band2	Band3	Band 4	Band 5	Band 6	Avg(3,4)
71.27	6.75	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
100.83	7.03	0.997365	0.997552	0.998621	0.998292	0.999674	1.000493	0.998457
130.39	5.45	0.996291	0.995549	0.994571	0.994247	0.992743	0.989822	0.994409
159.19	6.65	0.998868	1.000168	1.000824	1.001378	1.000892	0.999349	1.001101
188.89	6.72	1.006746	1.008088	1.009141	1.008252	1.007407	1.006821	1.008697
219.75	6.66	0.990854	0.992937	0.993760	0.994681	0.993468	0.990557	0.994221
249.38	7.10	0.988172	0.989013	0.990712	0.992368	0.990684	0.988944	0.991540
278.87	6.43	0.999481	1.000488	1.002171	1.002218	1.000371	0.996561	1.002194
308.36	5.70	0.998845	0.999266	0.999860	0.999473	0.997475	0.991503	0.999667
366.31	6.52	1.000542	1.003079	1.005813	1.004615	1.003530	1.000431	1.005214
395.73	6.69	1.001693	1.003233	1.005980	1.006086	1.005289	1.002660	1.006033
425.84	6.55	1.000651	1.003680	1.005722	1.005955	1.005020	1.001922	1.005838
455.33	7.03	1.006980	1.009688	1.012697	1.013662	1.011459	1.009191	1.013180
484.89	6.73	0.993474	0.994403	0.997869	0.998145	0.997434	0.994076	0.998007
514.38	4.88	0.992482	0.992949	0.994252	0.993983	0.990158	0.983473	0.994117
544.20	7.38	0.987405	0.989255	0.994314	0.994554	0.993703	0.991148	0.994434
572.73	7.01	1.016119	1.018616	1.022302	1.022770	1.021337	1.017727	1.022536
603.38	6.92	0.988278	0.991423	0.994742	0.995517	0.992235	0.988883	0.995130

Table 4. SeaWiFS lunar measurements normalized to the average for bands 3 and 4. These are the data used for the calculation of the modified correction. The values for bands 1 and 6 are plotted in Figure 2 along with the lunar phase angles.

Days After First Image	Lunar Phase Angle (deg)	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
71.27	6.75	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
100.83	7.03	0.998907	0.999094	1.000165	0.999835	1.001219	1.002039
130.39	5.45	1.001893	1.001147	1.000163	0.999837	0.998325	0.995388
159.19	6.65	0.997770	0.999068	0.999723	1.000277	0.999792	0.998250
188.89	6.72	0.998066	0.999397	1.000441	0.999559	0.998721	0.998141
219.75	6.66	0.996614	0.998709	0.999537	1.000463	0.999244	0.996315
249.38	7.10	0.996603	0.997451	0.999165	1.000835	0.999137	0.997382
278.87	6.43	0.997293	0.998297	0.999977	1.000023	0.998180	0.994379
308.36	5.70	0.999178	0.999600	1.000194	0.999806	0.997807	0.991834
366.31	6.52	0.995352	0.997876	1.000596	0.999404	0.998325	0.995242
395.73	6.69	0.995686	0.997217	0.999947	1.000053	0.999260	0.996647
425.84	6.55	0.994843	0.997855	0.999884	1.000116	0.999187	0.996106
455.33	7.03	0.993881	0.996554	0.999524	1.000476	0.998301	0.996063
484.89	6.73	0.995458	0.996389	0.999861	1.000139	0.999426	0.996061
514.38	4.88	0.998355	0.998824	1.000135	0.999865	0.996017	0.989293
544.20	7.38	0.992932	0.994793	0.999879	1.000121	0.999265	0.996695
572.73	7.01	0.993725	0.996166	0.999771	1.000229	0.998828	0.995297
603.38	6.92	0.993115	0.996275	0.999611	1.000389	0.997091	0.993723

Table 5. Coefficients used in the lunar reflectance correction in Equation 4. The coefficients a_0, a_1, and a_2 in the equation remain unchanged.

Band	δ_B (deg^{-1})
1	-2.1232×10^{-3}
2	-1.1984×10^{-3}
3	-0.1664×10^{-3}
4	0.1635×10^{-3}
5	1.0890×10^{-3}
6	2.8502×10^{-3}
7	4.0100×10^{-3}
8	4.4567×10^{-3}

Table 6. Calculated values of $[1-\delta_B(\theta-7)]$ for the SeaWiFS lunar measurements through 30 May 1999.

Days After First Image	Lunar Phase Angle (deg)	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
71.27	6.75	0.999469	0.999700	0.999958	1.000041	1.000272	1.000713
100.83	7.03	1.000064	1.000036	1.000005	0.999995	0.999967	0.999914
130.39	5.45	0.996709	0.998142	0.999742	1.000253	1.001688	1.004418
159.19	6.65	0.999257	0.999581	0.999942	1.000057	1.000381	1.000998
188.89	6.72	0.999406	0.999664	0.999953	1.000046	1.000305	1.000798
219.75	6.66	0.999278	0.999593	0.999943	1.000056	1.000370	1.000969
249.38	7.10	1.000212	1.000120	1.000017	0.999984	0.999891	0.999715
278.87	6.43	0.998790	0.999317	0.999905	1.000093	1.000621	1.001625
308.36	5.70	0.997240	0.998442	0.999784	1.000213	1.001416	1.003705
366.31	6.52	0.998981	0.999425	0.999920	1.000078	1.000523	1.001368
395.73	6.69	0.999342	0.999628	0.999948	1.000051	1.000338	1.000884
425.84	6.55	0.999045	0.999461	0.999925	1.000074	1.000490	1.001283
455.33	7.03	1.000064	1.000036	1.000005	0.999995	0.999967	0.999914
484.89	6.73	0.999427	0.999676	0.999955	1.000044	1.000294	1.000770
514.38	4.88	0.995499	0.997459	0.999647	1.000347	1.002309	1.006042
544.20	7.38	1.000807	1.000455	1.000063	0.999938	0.999586	0.998917
572.73	7.01	1.000021	1.000012	1.000002	0.999998	0.999989	0.999971
603.38	6.92	0.999830	0.999904	0.999987	1.000013	1.000087	1.000228
633.21	7.95	1.002017	1.001138	1.000158	0.999845	0.998965	0.997292

Table 7. Revised values for the SeaWiFS lunar measurements. The modification, $[1-\delta_B(\theta-7)]$, has been applied. These values are plotted in Figure 4.

Days After First Image	Lunar Phase Angle (deg)	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
71.27	6.75	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
100.83	7.03	0.999501	0.999429	1.000211	0.999789	1.000913	1.001240
130.39	5.45	0.999128	0.999588	0.999948	1.000052	0.999740	0.999075
159.19	6.65	0.997558	0.998948	0.999707	1.000293	0.999901	0.998535
188.89	6.72	0.998002	0.999361	1.000436	0.999564	0.998754	0.998226
219.75	6.66	0.996424	0.998602	0.999522	1.000478	0.999342	0.996570
249.38	7.10	0.997344	0.997869	0.999223	1.000777	0.998755	0.996387
278.87	6.43	0.996615	0.997915	0.999924	1.000076	0.998529	0.995286
308.36	5.70	0.996951	0.998343	1.000020	0.999980	0.998950	0.994802
366.31	6.52	0.994866	0.997601	1.000558	0.999442	0.998575	0.995894
395.73	6.69	0.995559	0.997145	0.999937	1.000063	0.999326	0.996817
425.84	6.55	0.994421	0.997616	0.999851	1.000149	0.999405	0.996674
455.33	7.03	0.994471	0.996888	0.999570	1.000430	0.997997	0.995269
484.89	6.73	0.995416	0.996365	0.999858	1.000142	0.999448	0.996118
514.38	4.88	0.994392	0.996588	0.999827	1.000173	0.998048	0.994565
544.20	7.38	0.994260	0.995543	0.999983	1.000017	0.998579	0.994906
572.73	7.01	0.994273	0.996476	0.999814	1.000186	0.998545	0.994560
603.38	6.92	0.993473	0.996478	0.999639	1.000361	0.996907	0.993241
633.21	7.95	0.994110	0.996089	0.999204	1.000796	0.999447	0.993802

Table 8. Summed spectral radiances for the SeaWiFS lunar measurements. The units for the summed radiances (S_{CORR}) are mW cm^{-2} sr^{-1} um^{-1}. The radiances in the table have been corrected for the set of factors in Barnes (1998, 1999), including the original lunar reflectance correction factor, k_3.

Days After First Image	Lunar Phase Angle (deg)	S_{CORR} Band 7	S_{CORR} Band 8
71.27	6.75	455.260	361.790
100.83	7.03	454.704	359.996
130.39	5.45	448.734	353.316
159.19	6.65	453.200	356.241
188.89	6.72	456.104	356.177
219.75	6.66	448.394	348.627
249.38	7.10	446.809	345.917
278.87	6.43	448.841	346.885
308.36	5.70	446.030	343.645
366.31	6.52	449.921	345.369
395.73	6.69	450.825	345.543
425.84	6.55	449.983	345.046
455.33	7.03	453.742	347.740
484.89	6.73	447.082	342.016
514.38	4.88	440.613	335.813
544.20	7.38	444.851	338.657
572.73	7.01	456.322	346.835
603.38	6.92	442.742	335.340

Table 9. Normalized spectral radiances for the SeaWiFS Lunar Measurements. The radiances have been set to unity at the date of the first lunar measurement. The rightmost column gives the average value for bands 3 and 4.

Days After First Image	Lunar Phase Angle (deg)	Band 7	Band 8	Avg(3,4)
71.27	6.75	1.000000	1.000000	1.000000
100.83	7.03	0.998778	0.995042	0.998457
130.39	5.45	0.985665	0.976576	0.994409
159.19	6.65	0.995474	0.984663	1.001101
188.89	6.72	1.001855	0.984484	1.008697
219.75	6.66	0.984919	0.963618	0.994221
249.38	7.10	0.981437	0.956126	0.991540
278.87	6.43	0.985901	0.958803	1.002194
308.36	5.70	0.979725	0.949847	0.999667
366.31	6.52	0.988273	0.954611	1.005214
395.73	6.69	0.990258	0.955093	1.006033
425.84	6.55	0.988410	0.953720	1.005838
455.33	7.03	0.996665	0.961165	1.013180
484.89	6.73	0.982037	0.945345	0.998007
514.38	4.88	0.967827	0.928199	0.994117
544.20	7.38	0.977135	0.936061	0.994434
572.73	7.01	1.002333	0.958663	1.022536
603.38	6.92	0.972503	0.926892	0.995130

Table 10. SeaWiFS lunar measurements normalized to the average for bands 3 and 4. These are the data used for the calculation of the modified correction.

Days After First Image	Lunar Phase Angle (deg)	Band 7	Band 8
71.27	6.75	1.000000	1.000000
100.83	7.03	1.000322	0.996580
130.39	5.45	0.991207	0.982067
159.19	6.65	0.994379	0.983580
188.89	6.72	0.993217	0.975997
219.75	6.66	0.990644	0.969219
249.38	7.10	0.989811	0.964283
278.87	6.43	0.983742	0.956704
308.36	5.70	0.980052	0.950163
366.31	6.52	0.983147	0.949659
395.73	6.69	0.984319	0.949366
425.84	6.55	0.982673	0.948184
455.33	7.03	0.983700	0.948662
484.89	6.73	0.983998	0.947233
514.38	4.88	0.973554	0.933692
544.20	7.38	0.982605	0.941300
572.73	7.01	0.980243	0.937535
603.38	6.92	0.977262	0.931428

Table 11. Coefficients for the fitted curves in Figure 6. For each band there is a set of two curves. The start date and end date for each curve in each set are given as days after the first image.

Band	d_0 (dimensionless)	d_1 (day^{-1})	d_2 (day^{-2})	Start Date	End Date
7	1.00886	-1.0983×10^{-4}	1.1320×10^{-7}	71	485
7	0.97359	0	0	485	604
8	1.02424	-3.2525×10^{-4}	3.3942×10^{-7}	71	435
8	0.89060	1.8430×10^{-4}	-2.4408×10^{-7}	435	604

Table 12. Calculated values of $[1-\delta_B(\theta-7)]$ for the SeaWiFS lunar measurements through 30 May 1999.

Days After First Image	Lunar Phase Angle (deg)	Band 7	Band 8
71.27	6.75	1.001003	1.001114
100.83	7.03	0.999880	0.999866
130.39	5.45	1.006216	1.006908
159.19	6.65	1.001404	1.001560
188.89	6.72	1.001123	1.001248
219.75	6.66	1.001363	1.001515
249.38	7.10	0.999599	0.999554
278.87	6.43	1.002286	1.002540
308.36	5.70	1.005213	1.005794
366.31	6.52	1.001925	1.002139
395.73	6.69	1.001243	1.001382
425.84	6.55	1.001805	1.002006
455.33	7.03	0.999880	0.999866
484.89	6.73	1.001083	1.001203
514.38	4.88	1.008501	1.009448
544.20	7.38	0.998476	0.998306
572.73	7.01	0.999960	0.999955
603.38	6.92	1.000321	1.000357
633.21	7.95	0.996191	0.995766

Table 13. Revised values for the SeaWiFS lunar measurements. The modification, $[1-\delta_B(\theta-7)]$, has been applied.

Days After First Image	Lunar Phase Angle (deg)	Band 7	Band 8
71.27	6.75	1.000000	1.000000
100.83	7.03	0.999200	0.995338
130.39	5.45	0.996369	0.987751
159.19	6.65	0.994778	0.984018
188.89	6.72	0.993336	0.976127
219.75	6.66	0.991001	0.969608
249.38	7.10	0.988423	0.962781
278.87	6.43	0.985004	0.958067
308.36	5.70	0.984174	0.954605
366.31	6.52	0.984053	0.950632
395.73	6.69	0.984556	0.949619
425.84	6.55	0.983460	0.949029
455.33	7.03	0.982597	0.947480
484.89	6.73	0.984077	0.947317
514.38	4.88	0.980847	0.941465
544.20	7.38	0.980125	0.938660
572.73	7.01	0.979222	0.936450
603.38	6.92	0.976597	0.930723
633.21	7.95	0.977820	0.929505

Table 14. Coefficients for the fitted curves in Figure 8. For each band there is a set of two curves. The start date and end date for each curve in each set are given as days after the first SeaWiFS image on orbit.

Band	f_0 (dimensionless)	f_1 (day^{-1})	f_2 (day^{-2})	Start Date	End Date
7	1.00885	-1.1312×10^{-4}	1.2441×10^{-7}	71	395
7	0.97783	4.3295×10^{-5}	-7.2745×10^{-8}	395	604
8	1.02426	-3.2862×10^{-4}	3.5088×10^{-7}	71	395
8	0.92400	1.6138×10^{-4}	-2.4703×10^{-7}	395	604

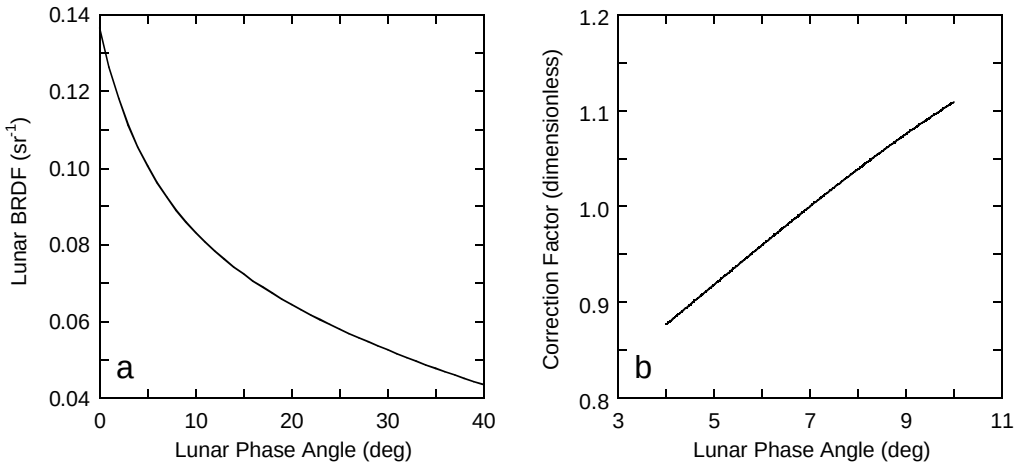

Figure 1. Disk integrated reflectance versus lunar phase angle.

a. Disk integrated lunar reflectance (BRDF) from 0° to 40° phase.
b. Lunar reflectance normalizing factor calculated with Equation (8). The value at 7° phase angle is unity.

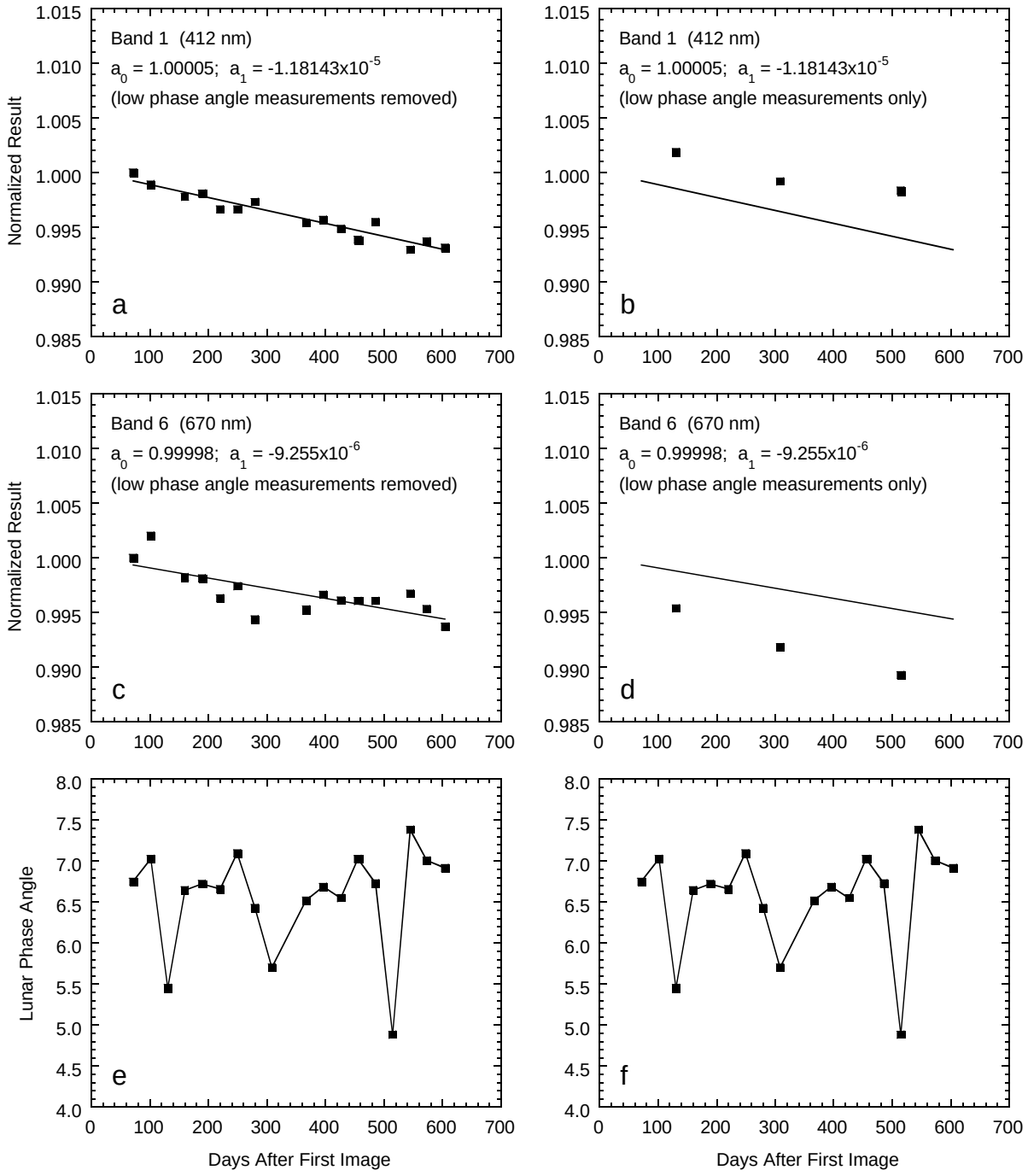

Figure 2. Changes in the radiometric sensitivities of SeaWiFS bands 1 and 6.

a. Trends for band 1 based on lunar measurements with phase angles within 1° of 7°. The fitted curve is a linear regression.
b. Results for lunar measurements with phase angles more than 1° from 7°. The fitted curve comes from Figure 1a.
c. Same as Figure 1a, except for band 6.
d. Same as Figure 1b, except for band 6.
e. Lunar phase angles for the SeaWiFS measurements.
f. Lunar phase angles for the SeaWiFS measurements.

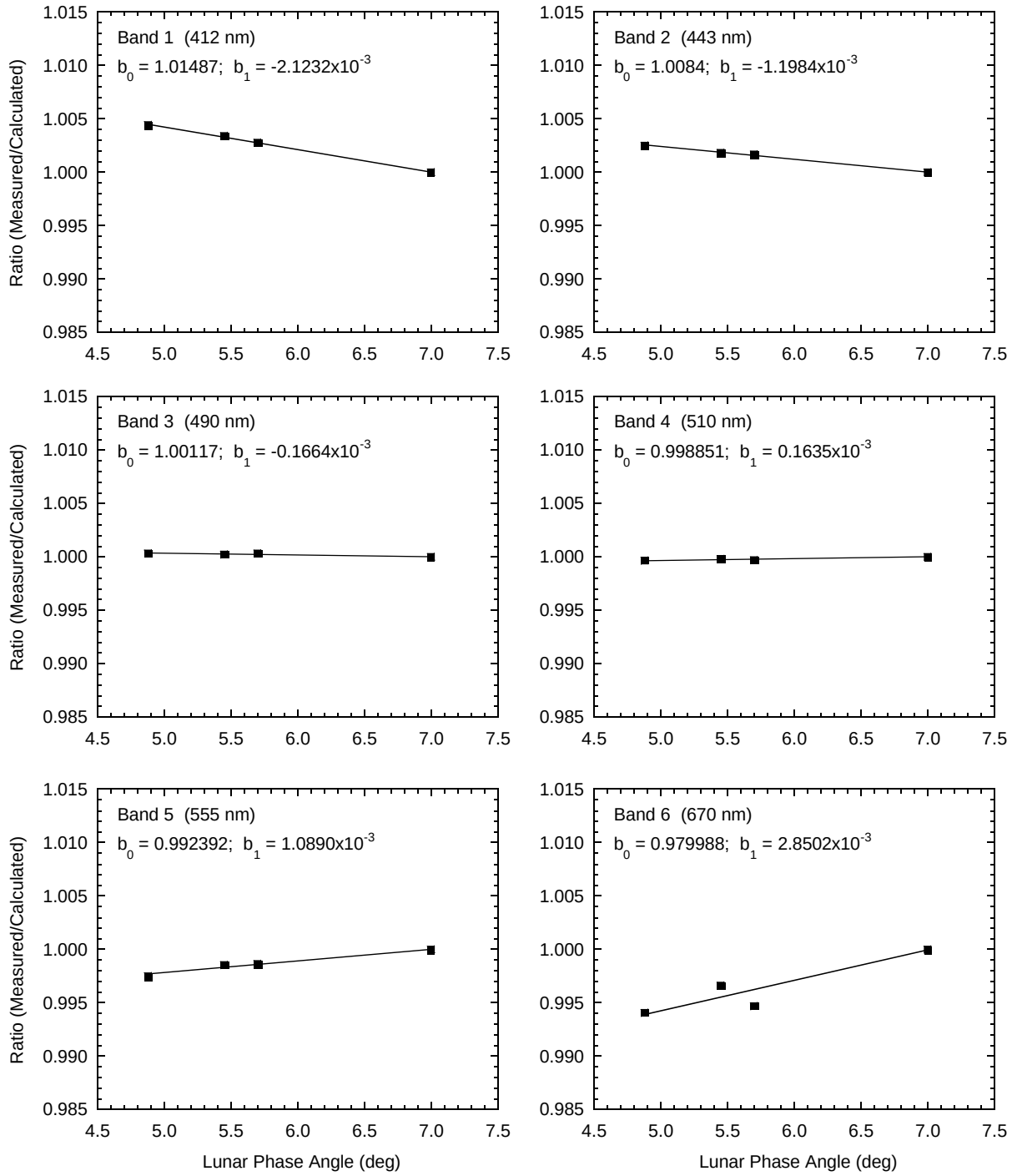

Figure 3. Differences of the lunar measurements from 13 January 1998, 10 July 1998, and 1 February 1999 from the trend lines for SeaWiFS bands 1 through 6. The lines in each panel are linear regressions to the data, and the coefficients in each panel give the intercept and slope for the line.

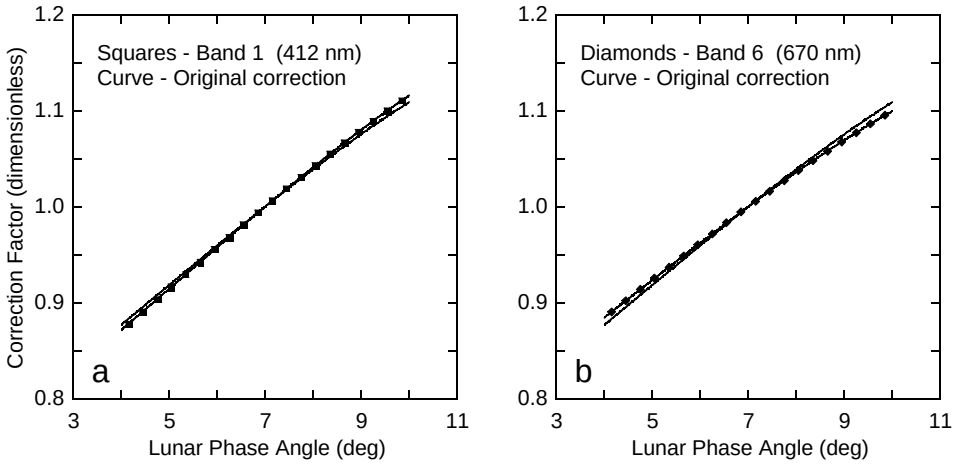

Figure 4. Modified lunar reflectance corrections for SeaWiFS bands 1 and 6. For each panel, the unmarked curve gives the original correction from Barnes (1998, 1999).

a. Correction for SeaWiFS band 1 (412 nm)
b. Correction for SeaWiFS band 6 (670 nm)

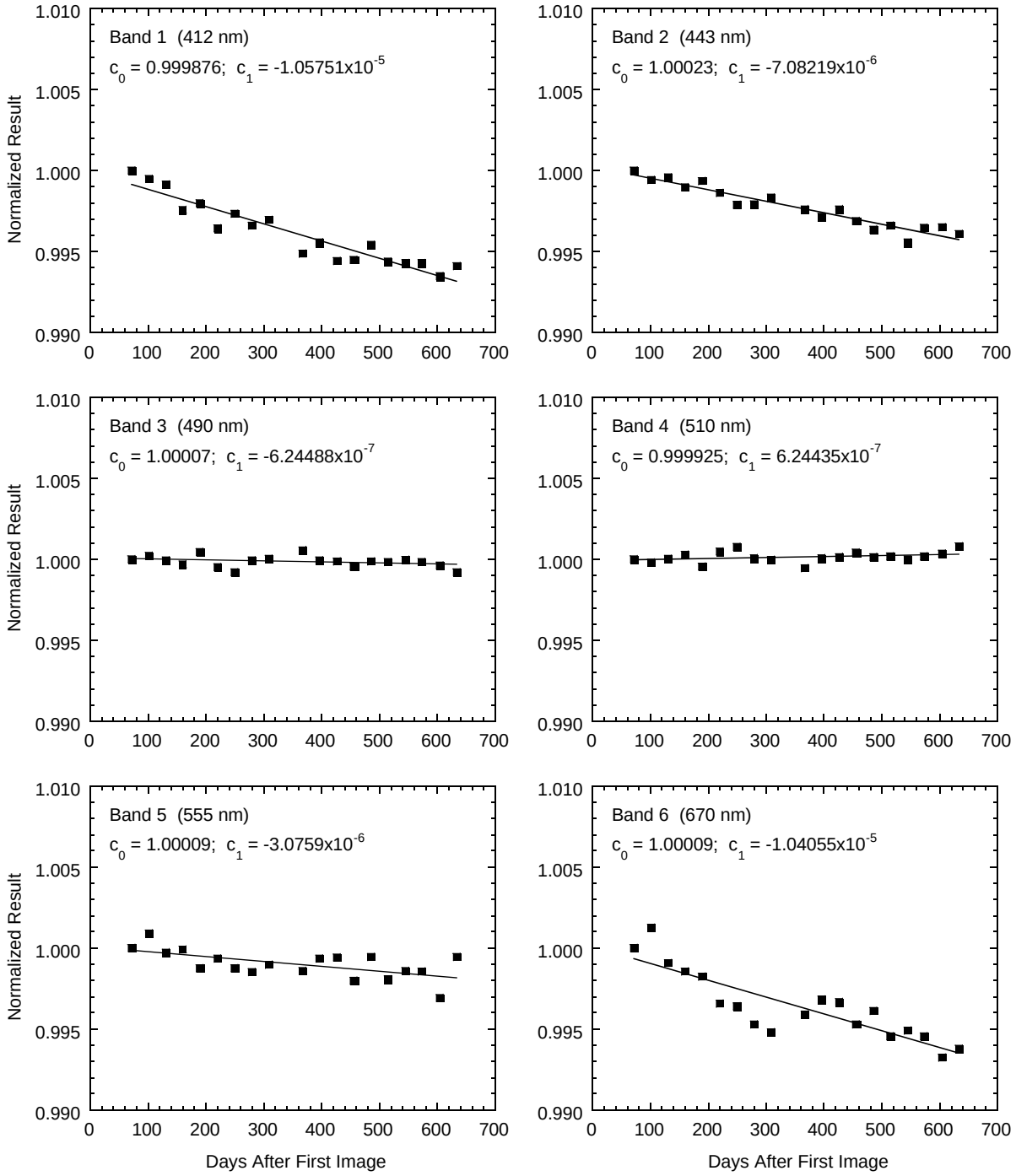

Figure 5. Changes in the radiometric sensitivities of SeaWiFS bands 1 through 6 from the lunar measurements. The modification to the lunar reflectance corrections, $[1-\delta_B(\theta-7)]$, has been applied. Each panel includes all of the lunar measurements from 14 November 1997 through 30 May 1999.

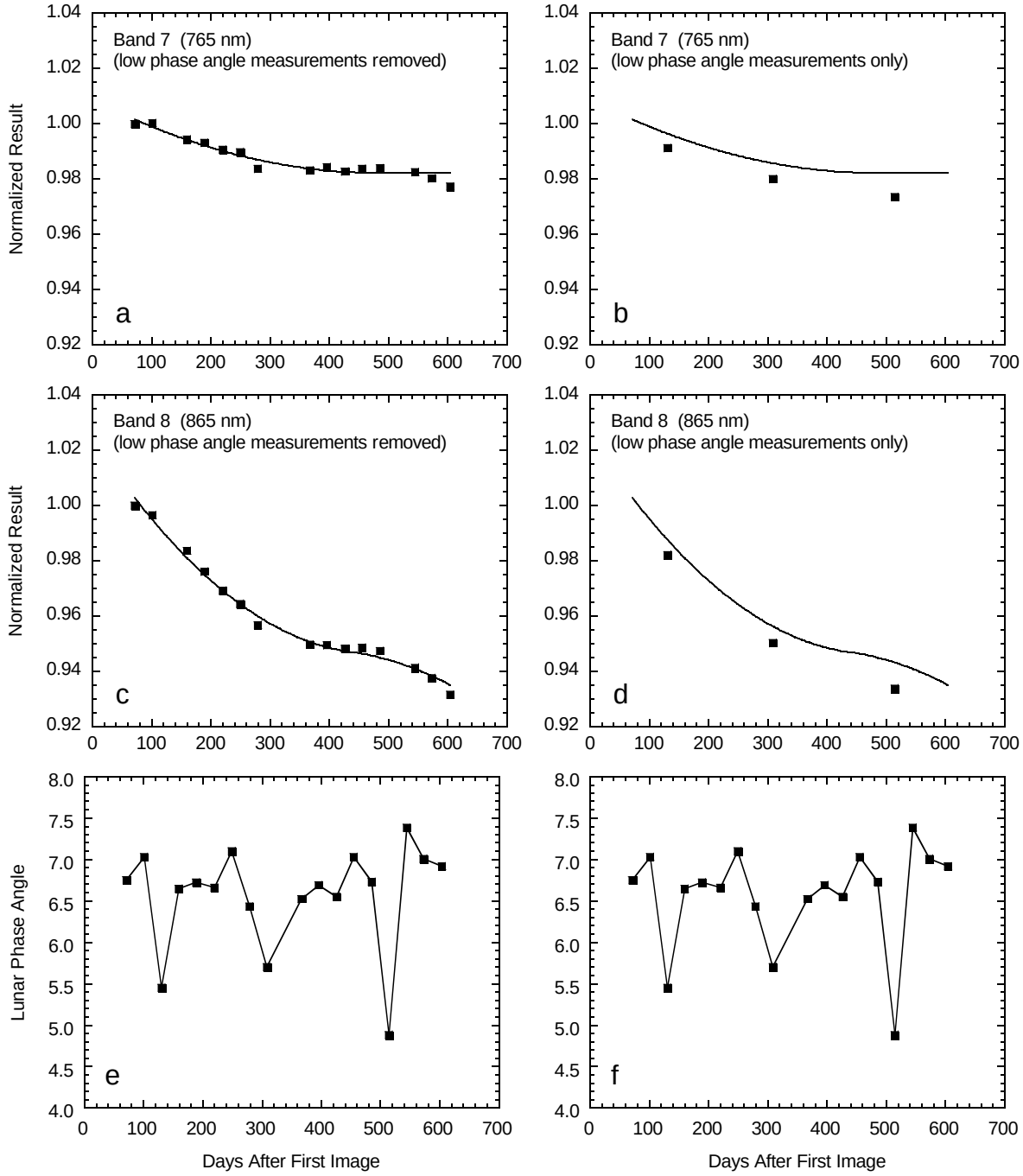

Figure 6. Changes in the radiometric sensitivities of SeaWiFS bands 7 and 8.

a. Trends for band 7 based on lunar measurements with phase angles within 1° of 7°. The fitted line is a combination of two curves.
b. Results for lunar measurements with phase angles more than 1° from 7°. The fitted line comes from Figure 6a.
c. Same as Figure 6a, except for band 8.
d. Same as Figure 6b, except for band 8.
e. Lunar phase angles for the SeaWiFS measurements.
f. Lunar phase angles for the SeaWiFS measurements.

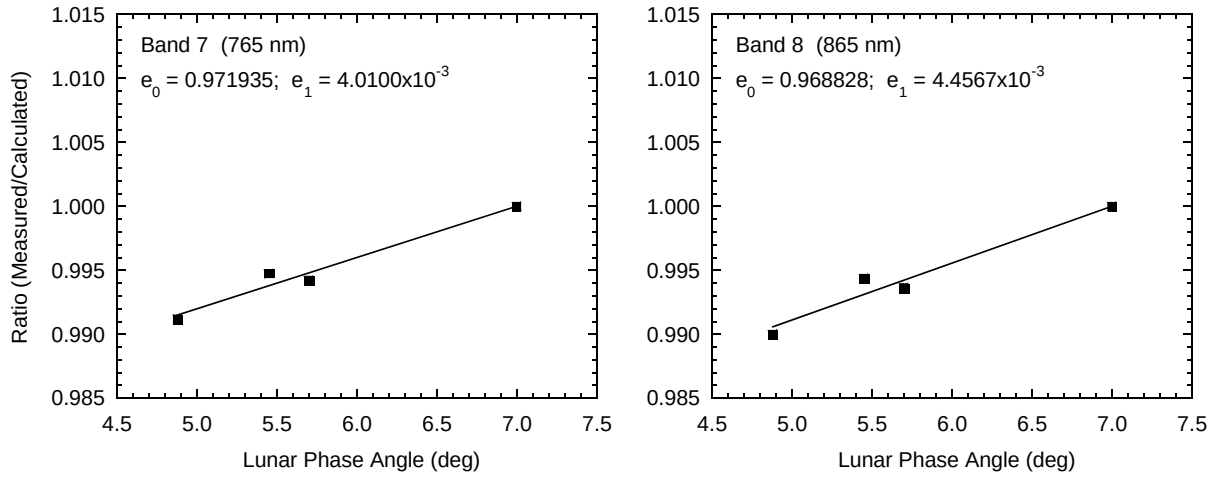

Figure 7. Differences of the lunar measurements from 13 January 1998, 10 July 1998, and 1 February 1999 from the trend lines for SeaWiFS bands 7 and 8. The lines in each panel are linear regressions to the data, and the coefficients in each panel give the intercept and slope for the line.

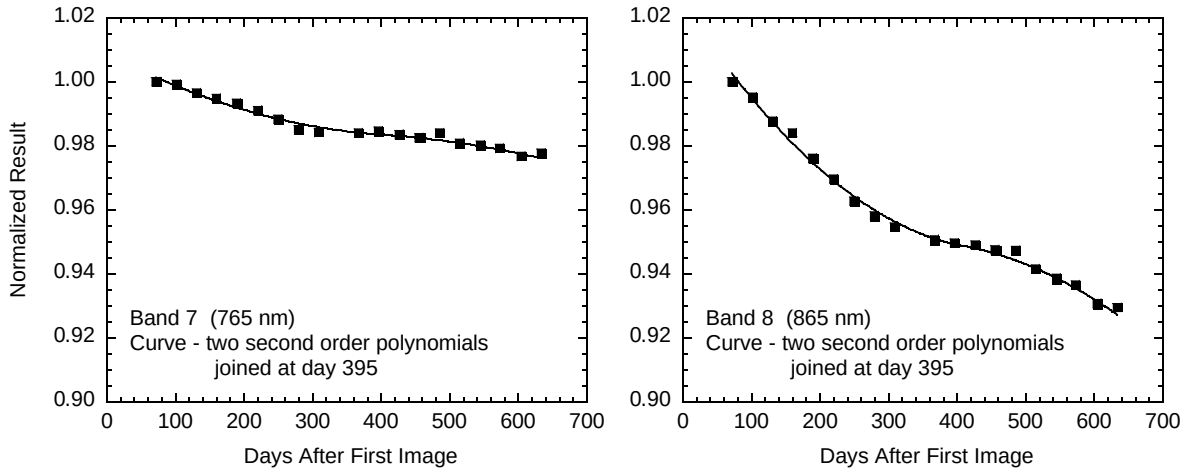

Figure 8. Changes in the radiometric sensitivities of SeaWiFS bands 7 and 8 from the lunar measurements. The modification to the lunar reflectance corrections, $[1-\delta_B(\theta-7)]$, has been applied. Each panel includes all of the lunar measurements from 14 November 1997 through 30 May 1999.

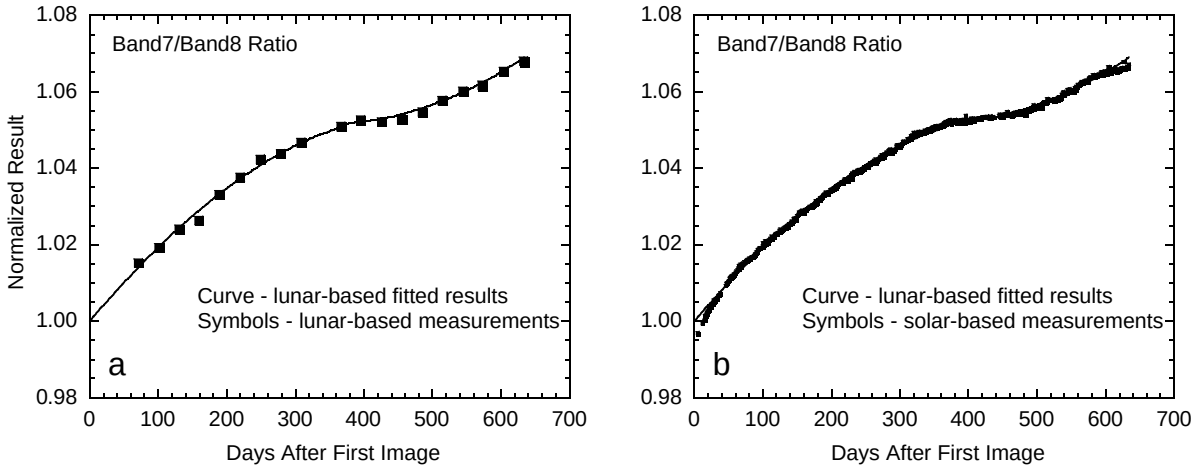

Figure 9. Band7/Band8 ratios from the lunar and solar-based measurements.

a. Lunar-based measurements. The symbols give the measured ratios and the line gives the best fit curve.
b. Solar-based measurements. The symbols give the measured ratios, and the line gives the best fit curve from the lunar measurements. The solar-based values have been multiplied by 0.9969 to obtain the best agreement with the lunar-based curve.